THE TRAJECTORY CONTROL STRATEGIES FOR AKATSUKI RE-INSERTION INTO THE VENUS ORBIT

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Abstract: *The Japanese Venus explorer "Akatsuki (PLANET-C)", which now rotates about the Sun, will approach to Venus again in 2015. For the Venus orbit re-insertion, several trajectory strategies were devised. This paper introduces the difficulties we faced in redesigning the trajectory of Akatsuki after the failure of the first Venus Orbit Insertion (VOI) in 2010 and reports some newly devised trajectory control strategies including the Gravity Brake Method, which will make the most of the solar perturbations to conduct the Venus orbit insertion for the second time.*

Keywords: *Venus explorer, Akatsuki (PLANET-C), Venus orbit re-insertion, solar perturbations, Gravity Brake Method*

1. Introduction

The Japanese Venus explorer "Akatsuki (PLANET-C)" was launched on May 20, 2010 (UT) in order to address the mysterious Venusian atmosphere [1] and approached Venus at the altitude of 550 km on Dec. 7, 2010 as scheduled. However, it made a flyby of Venus, for it couldn't perform enough deceleration because of a defect of its propulsion system. It now rotates about the Sun with its perihelion radius of 90 million km and its aphelion radius of 110 million km [2]. The characteristic of Venus is that its axial tilt is 177.4 degrees. This means that the Earth rotates counter-clockwise when seen from the North (direct) and that Venus does clockwise (retrograde). The Venusian atmosphere also rotates in the same manner as Venus in retrograde direction.

As observation requirements of the Venus circular orbit, two things should be considered: one is that the orbital plane is close to the Venus equator and the other is that the rotation direction is the same as the Super Rotation of Venus atmosphere. Hence, from the view points of observation, it is desired that Akatsuki is inserted to the retrograde orbit. However, there is a difficulty in the present trajectory, once failed in VOI. That is, if Akatsuki is inserted into the retrograde orbit at the first re-encounter with Venus, the periapsis decreases rapidly and intersects Venus. This is because Akatsuki passes through the area where the solar perturbations (SP) act as deceleration shortly after the orbit insertion. Although there are some cases in which Akatsuki can maintain the altitude in direct orbit, in none of the cases the periapsis altitude cannot be maintained in the retrograde orbit because of the SP.

In order to overcome these difficulties, a trajectory strategy, named Gravity Brake Method (GBM), is devised. The key idea in this method is the use of the SP at a far distance. Initially, though we insert a spacecraft to the direct orbit, we choose the apoapsis altitude of 1 million km. Then, the rotating direction of orbit transits from direct to retrograde. This is all done by the SP which has prevented a probe from maintaining the periapsis altitude thus far. After the spacecraft rotates in retrograde direction, it flies in the acceleration area of the SP to keep the periapsis altitude. Aside from the GBM, another method, Hohmann Transfer Method (HTM), is also prepared. A probe performs a large deceleration maneuver before the first Venus re-encounter to move the crossing point to near the apoapsis. This is effective in changing the approach angle to Venus so that the circular orbit starts from the acceleration area to prevent a probe from intersecting Venus. This paper presents the details of the result of trajectory design of Akatsuki which will conduct the Venus orbit insertion for the second time.

2. Current Orbit

2.1. Venus Orbit Insertion (VOI) in 2010

Akatsuki was launched on May 20, 2010 and reached Venus at an altitude of 550 km on December 7, 2010 after four orbital correction maneuvers shown in Fig. 1. At the Venus Orbit Insertion (VOI-1), the Orbit Maneuvering Engine (OME) was supposed to perform retrograde maneuver of 748.3 m/s for 717.5 seconds. However, it experienced a trouble of an explorer propulsion system and made a flyby of Venus. Figure 2 and Tab. 1 show the plan and its result of VOI-1. The maneuver direction and duration were evaluated by fitting the orbital elements after VOI-1, assuming that Akatsuki started the maneuver on schedule with thrust force 100%. Whereas it is different from the burning duration obtained by the telemetry (158 seconds), the orbital change caused by the attitude control by Reaction Control System (RCS) later on is also included for this evaluation.

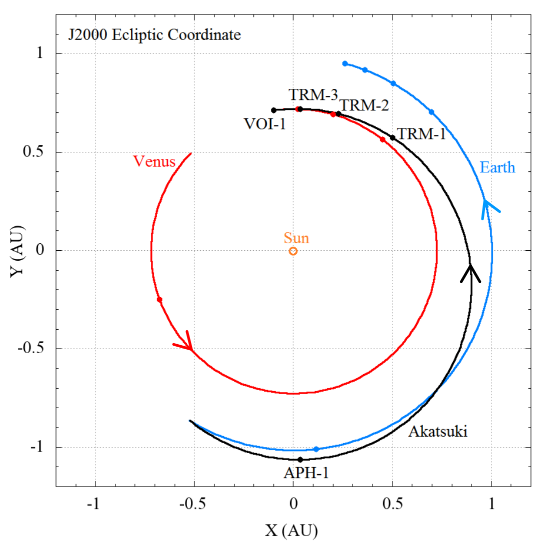


Figure 1. Trajectory from Launch to VOI-1

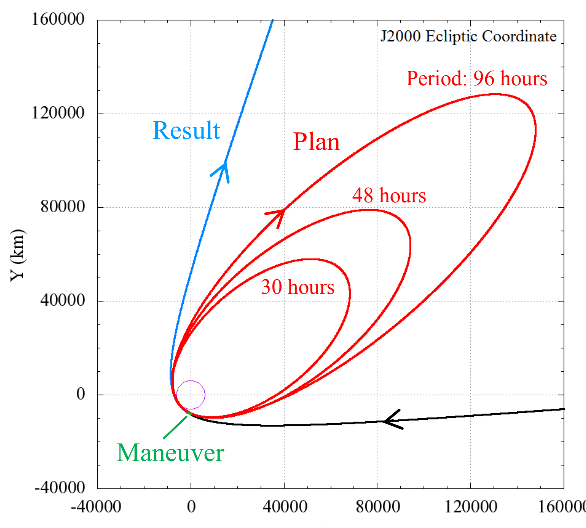


Figure 2. Planned Trajectory and Result

Table 1. Maneuver Evaluation of VOI-1

	⊿V magnitude [m/s]	⊿V duration [sec]	Direction Error [deg]	
			in plane	out of plane
Plan (ICV48I3 (Dec. 5))	748.3	718.0		
Result (Dec. 9)	134.8	142.5	-0.14	+1.14

2.2. Period Adjustment in 2011 to Re-Encounter Venus

In order to decide whether the OME can be used, two Test Maneuvers (TMs) of OME were conducted in September 2011. Unfortunately, the force was not large enough as expected, so that the rest of orbital maneuvers would be performed by RCS. After the TMs, for the purpose to lighten the spacecraft, all the oxidizer, which is no need for RCS, was disposed in direction of deceleration to take advantages of it as orbital maneuvers. Since Akatsuki rotates in 203 days, it approaches Venus in January 2017. However, if it performs a maneuver of about 240 m/s at perihelion, the encounter timing will be earlier and it also works in a good way in reducing the relative velocity to Venus because the encounter point moves to near the aphelion [3]. Hence, it performed three retrograde maneuvers and the encounter date became November 22, 2015. Table 2 shows the maneuver record after VOI-1 and the orbital changes caused by the maneuvers are shown in Fig. 3.

Table 2. Maneuvers after VOI-1

Events	Time (UTC)	Duration [sec]	Engine	Maneuver Amount [m/s]				Maneuver Direction [deg]		
				Total	Radial	In-track	Crosstrack	R.A.	Dec.	Error
OME Test Maneuver 1 (TM1)	7 Sep 2011 2:50:00	2.0	OME	0.7	0.0	0.0	0.7	277.4	68.2	-
OME Test Maneuver 2 (TM2)	14 Sep 2011 2:50:00	5.0	OME	0.6	0.0	0.0	0.6	289.7	58.0	-
Disposal of Oxidizer Test	30 Sep 2011 3:02:00	60.0	-	1.9	0.0	-1.9	0.0	239.9	-28.1	-
Disposal of Oxidizer 1 (DOX1)	6 Oct 2011 2:53:00	360.0	-	7.6	0.0	-7.6	0.0	173.9	9.0	-
Disposal of Oxidizer 2 (DOX2)	12 Oct 2011 3:23:00	540.0	-	16.2	0.0	-16.2	0.0	183.0	0.1	-
Disposal of Oxidizer 3 (DOX3)	13 Oct 2011 4:53:00	540.0	-							
Period Adjustment 1 (DV1)	1 Nov 2011 4:22:00	587.5	RCS	88.6 (90.0)	2.3 (0.0)	-85.6 (-86.2)	-22.7 (-25.8)	214.4 (213.2)	-27.3 (-28.8)	1.9
Period Adjustment 2 (DV2)	10 Nov 2011 4:37:00	544.0	RCS	90.6 (90.0)	-0.7 (0.0)	-87.6 (-86.2)	-23.1 (-25.8)	232.7 (232.0)	-33.0 (-34.9)	1.9
Period Adjustment 3 (DV3)	21 Nov 2011 4:57:00	342.125	RCS	63.5 (63.8)	-2.4 (0.0)	-59.7 (-60.0)	-21.4 (-21.6)	256.8 (256.7)	-42.8 (-42.9)	0.2

** The numbers in bracket are planned values.*

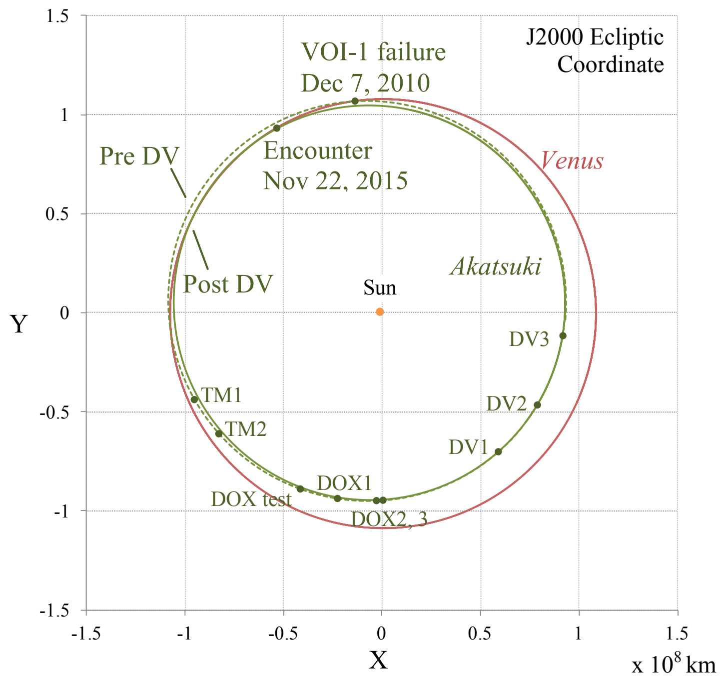


Figure 3. Orbital Changes by Period Adjustment

2.3. Venus Re-Encounter in 2015

The three maneuvers for the period adjustment made Akatsuki aphelion smaller by 3 million km and the period became approximately 199 days. It approaches Venus on November 22, 2015 from the described direction in Fig.4.

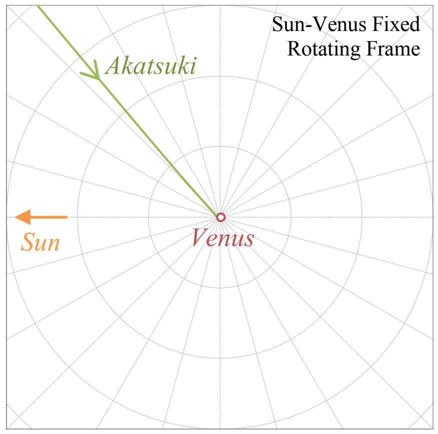


Figure 4. Approach Angle at Venus Re-Encounter in 2015

3. Venus Orbit Re-Insertion

3.1. Observation and System Requirements

Since the estimated residual propulsion is approximately 330 m/s by RCS, the apoapsis altitude in the Venus circular orbit has to be about 0.3 million km high. When it becomes high as 0.3 million km, the SP effect largely, so that in most of the simulation cases a spacecraft cannot maintain the periapsis and intersects Venus.

On the other hand, as observation and system requirements of the Venus circular orbit, the below four items should be considered; (a) and (b) are for observation and (c) and (d) are for probe system. There was another requirement, initially, that the orbital period should be 30 hours so that the explorer is synchronized with the angular velocity of the Venusian atmosphere. However, since the period of 30 hours cannot be realized with the present residual propulsion, we aim the apoapsis altitude as low as possible.

(a) Orbital plane : Close to the Venus equator
(b) Rotation direction: Retrograde (clockwise seen from the North, Same direction with the one of Venusian atmosphere)
(c) Umbra : Less than 90 minutes (constraints from batteries)
(d) Incident angle : Less than 13 degrees to the Akatsuki orbital plane (constrains from heat conditions)

In order to consider the strategies of Venus orbit insertion which satisfies the above requirements the most, the following cases are analyzed; (1) the cases to insert into the polar, direct or retrograde orbit at the first Venus encounter, (2) the cases to insert into the polar, direct or retrograde orbit at the second Venus encounter after one Venus swingby, and (3) the cases to insert into the polar, direct or retrograde orbit at the third Venus encounter after two Venus swingbys. The detailed results shown in Tab. 3 are summarized below.

Retrograde	: Cannot maintain the altitude of periapsis (The orbit intersects Venus).
Direct	: Can maintain the altitude of periapsis. However, the requirement (b) cannot be satisfied.
Polar	: Can maintain the altitude of periapsis. However, the requirement (a), (b) and (d) cannot be satisfied.

Table 3. Summary of the Orbit Re-Insertion: I

	1st Approach	2nd Approach	3rd Approach	Maintain Periapsis Altitude	System & Observation Requirements
(1)	VOI				
	(1-1) Retrograde			X	-
	(1-2) Direct			X	-
	(1-3) Polar			OK	NG (a,b,d)
(2a)	Swingby θ: 170 deg r: 16,000 km	→ VOI			
		(2a-1) Retrograde		X	-
		(2a-2) Direct		OK	NG (b)
		(2a-3) Polar		OK	NG (a,b,d)
(3a)		→ Swingby	→ VOI		
			(3a-1) Retrograde	X	-
			(3a-2) Direct	OK	NG (b)
			(3a-3) Polar	OK	NG (a,b,d)
(2b)	Swingby θ: 0 deg r: 150,000 km	→ VOI			
		(2b-1) Retrograde		X	-
		(2b-2) Direct		OK	NG (b)
		(2b-3) Polar		OK	NG (a,b,d)
(3b)		→ Swingby	→ VOI		
			(3b-1) Retrograde	X	-
			(3b-2) Direct	OK	NG (b)
			(3b-3) Polar	OK	NG (a,b,d)

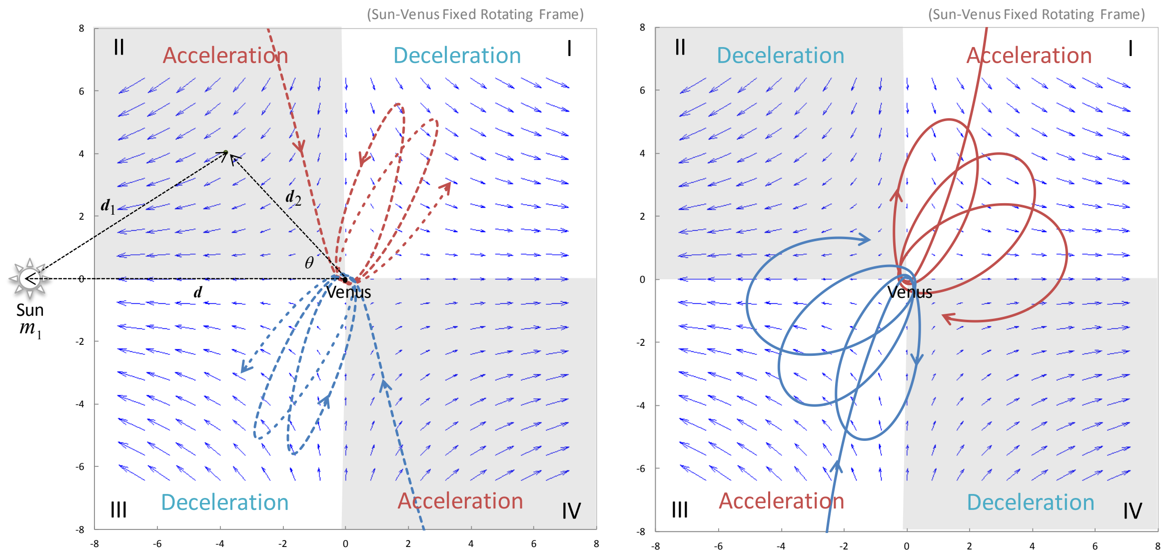
3.2. Solar Perturbations

The reason why each case causes the different result in maintaining the altitude of periapsis is the effect of the SP shortly after the VOI. Now, consider the case that there are three bodies; P_1 for the Sun, P_2 for Venus, and P_3 for a spacecraft. The mass of P_1 is m_1 and the position vector from P_1 to P_3 is given by $\boldsymbol{d}_1 = \boldsymbol{r}_3 - \boldsymbol{r}_1$. $\boldsymbol{d}_2 = \boldsymbol{r}_3 - \boldsymbol{r}_2$ and $\boldsymbol{d} = \boldsymbol{r}_1 - \boldsymbol{r}_1$ are also given in the same manner. Then the effect of solar perturbations $\boldsymbol{R}$ which affects to the spacecraft rotating about Venus is given by Eq.1 [4] [5].

$$\boldsymbol{R} = Gm_1\left(-\frac{\boldsymbol{d}_1}{d_1^3} - \frac{\boldsymbol{d}}{d^3}\right), \qquad \left|\boldsymbol{R}\right| = Gm_1\frac{d_2}{d^3}\sqrt{1+3\cos^2\theta} \tag{1}$$

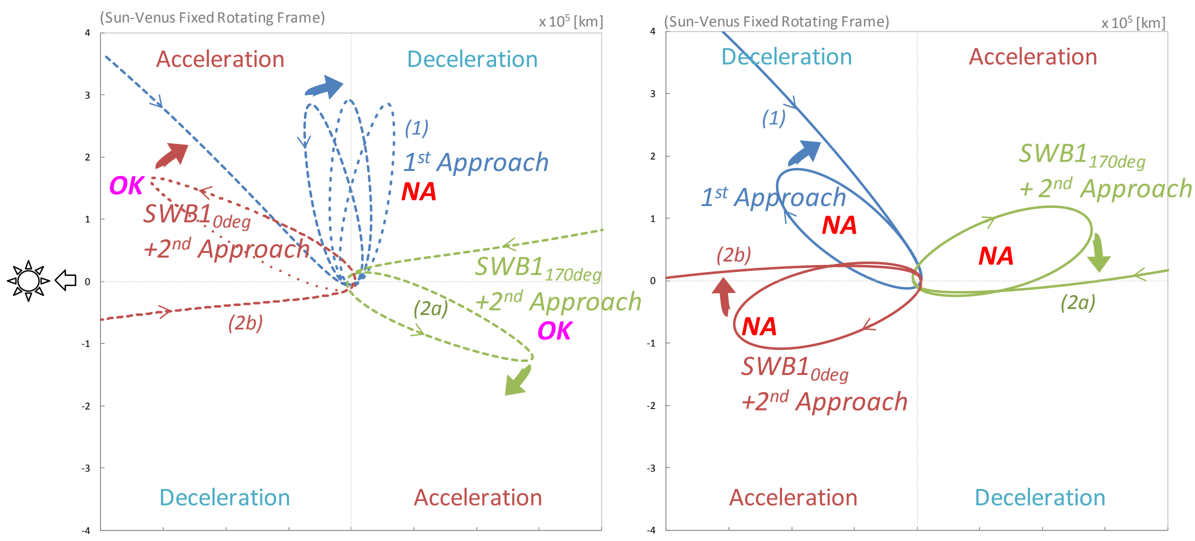
The vector field of the perturbations ***R*** is visualized in Fig. 5. Consider the case that a spacecraft is inserted into the retrograde orbit as shown in Fig.5 (b). While it flies in the first or the third quadrant, the altitude of periapsis doesn't decrease since the SP act in the way of acceleration at apoapsis. On the other hand, while it flies in the second or fourth quadrant, the altitude of periapsis decreases, for the SP do in the way of deceleration.

Figure 6 shows the approach angles of the Case (1), (2a), and (2b) in the section 3.1. in the Sun-Venus fixed rotating frame. As shown in Fig. 6 (b), when a probe is inserted into the retrograde orbit in none of the cases the periapsis cannot be maintained and intersects Venus because the SP act as deceleration after VOI.



(a) Insertion to Direct Orbit (b) Insertion to Retrograde Orbit

Figure 5. Acceleration and Deceleration Areas Caused by the SP



(a) Insertion to Direct Orbit (b) Insertion to Retrograde Orbit

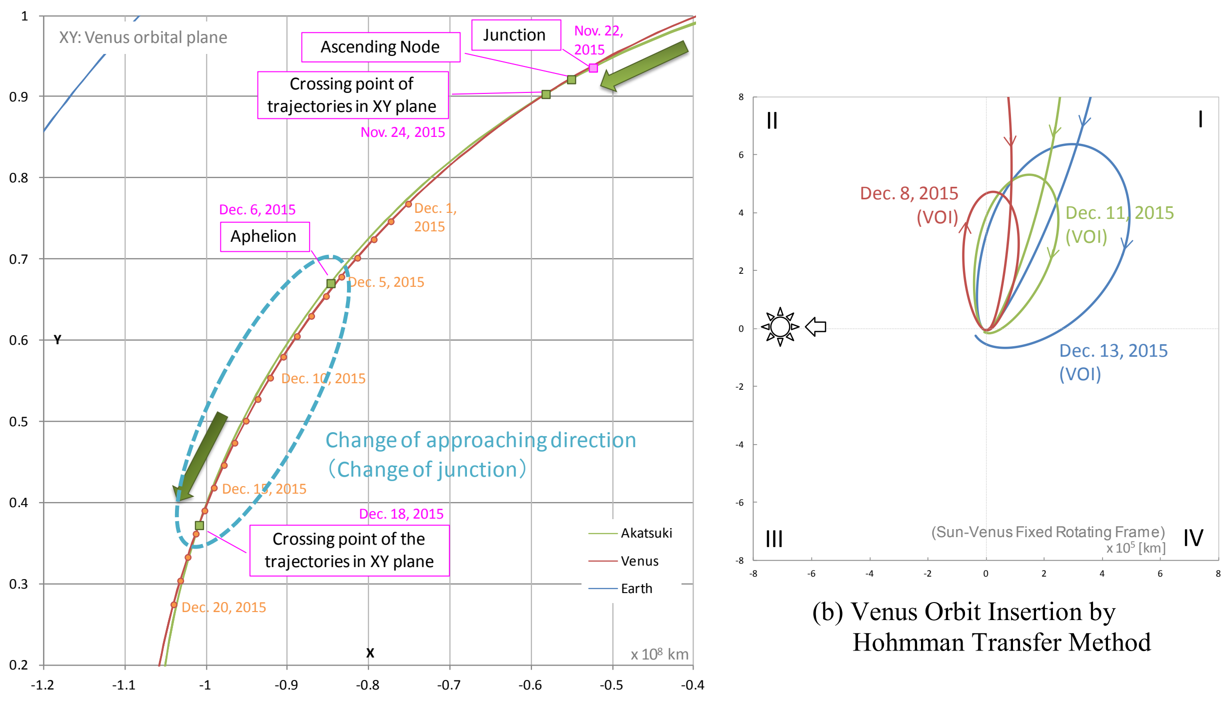
Figure 6. Approach Angles of the Case (1), (2a) and (2b)

3.3. Retrograde Orbit Insertion I (Hohmann Transfer Method)

Although there are some cases found in which a probe can maintain the altitude in the direct or polar orbit, there are no cases survived in the retrograde orbit. In order to prevent a probe from decreasing the altitude of periapsis in the retrograde orbit, the approach angle should be in acceleration area (in the first or the third quadrant). Akatsuki now approaches from inside of the Venus orbit (from the second quadrant) as shown in Fig. 4 and Fig. 7. In order to approach from outside of the Venus orbit (from the first quadrant), the approach angle should be changed as follows;

(i) Change of encounter point (approach from *inside* of the Venus orbit to *outside*),
(ii) Change of orbital plane (The encounter point should be a node.),
(iii) Orbital period (The encounter date should be December 5-13, 2015, not November 22).

Note that an additional maneuver of about 85 m/s will be necessary for those adjustments (i), (ii) and (iii) before the probe approaches Venus. Therefore, the final altitude of apoapsis becomes 0.1 million km higher than the one in the direct or the polar orbit.



(a) Relative Positions of Venus and Akatsuki

(b) Venus Orbit Insertion by Hohmman Transfer Method

Figure 7. Venus Orbit Re-Insertion by Hohmman Transfer Method

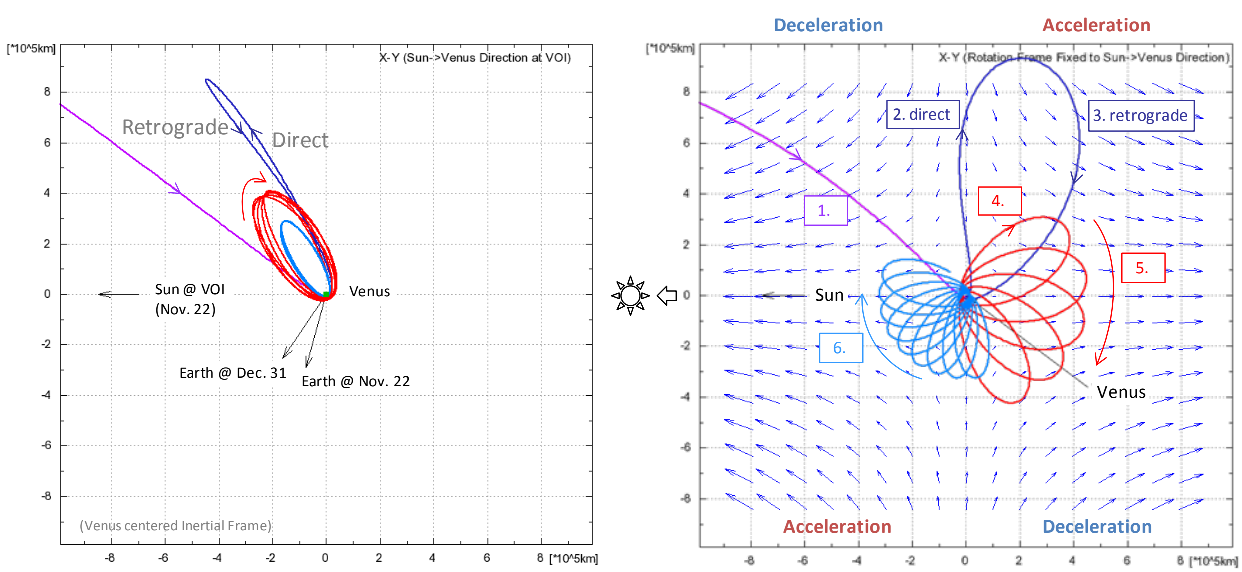
3.4. Retrograde Orbit Insertion II (Gravity Brake Method)

In order to lower the altitude of apoapsis even in the retrograde orbit, an insertion method named "Gravity Brake Method" is devised. It requires no additional maneuvers in the interplanetary transfer orbit and, moreover, allows Akatsuki to approach from the second quadrant as it stands now. In this method, the SP, which has prevented a probe from maintaining the altitude in the former sections, will be made the most of.

(1) The Orbit Transit from Direct to Retrograde
After a probe is inserted into the direct orbit and flies up to inside of the Hill radius of Venus, it rotates inversely from direct to retrograde by the effect of the SP (Trajectory 2 to 3 in Fig. 8(b).)

(2) 2-Step Deceleration Maneuvers
After it is transited to the retrograde orbit, the acceleration and deceleration areas are used to lower the apoapsis altitude the best by splitting the deceleration maneuvers in two steps. (Trajectory 5 and 6 in Fig. 8(b))

Here, the Hill radius means the largest radius inside of which a small object P_3 (spacecraft) rotating about P_2 (Venus) stays near P_2 under the influence of P_1 (the Sun) [4].



(a) GBM Trajectory in Inertial Frame (b) GBM Trajectory in Sun-Venus Fixed Rotating Frame

Figure 8. Venus Orbit Re-Insertion by the Gravity Brake Method

4. Summary of Venus Orbit Re-Insertion

The summary of the Venus orbit re-insertion is shown in Tab. 4. The four kinds of the insertion method, as shown in Tab. 5, were devised as conclusion: (A) polar, (B) direct, (C) retrograde (Hohmann Transfer Method) and (D) retrograde (Gravity Brake Method).

Table 4. Summary of the Orbit Re-Insertion: II

	1st approach	2nd approach	3rd approach	Venus Circular Orbit: maintaining altitude	Ha [km] x 1000	Period [days]
(1a)	VOI (approach from inside of Venus's orbit)					
	(1-1) Retrograde			X	—	—
	(1-2) Direct			X	—	—
	(1-3) Polar		A	OK	310	8.4
(1b)	VOI (Hohmann Transfer Method)					
	Retrograde		C	OK	420	13
(1c)	VOI (Gravity Brake Method)					
	Direct -> Retrograde		D	OK	310	8.4
(2a)	Swingby	→ VOI				
	θ 170°	(2a-1) Retrograde		X	—	—
	r 16,000km	(2a-2) Direct	B	OK	310	8.4
		(2a-3) Polar		OK	410	13
(3a)		→ Swingby	→ VOI			
			(3a-1) Retrograde	X	—	—
			(3a-2) Direct	OK	310	8.4
			(3a-3) Polar	OK	410	13
(2b)	Swingby	→ VOI				
	θ 0°	(2b-1) Retrograde		X	—	—
	r 150,000km	(2b-2) Direct		OK	410	13
		(2b-3) Polar		OK	410	13
(3b)		→ Swingby	→ VOI			
			(3b-1) Retrograde	X	—	—
			(3b-2) Direct	OK	410	13
			(3b-3) Polar	OK	410	13

** Maneuver amounts are all the same: 285 m/s, impulsive.*

Table 5. Options of Re-Insertion Method

No	Orbit	VOI date	Apoapsis Alt.
A	Polar	November 22, 2015	0.3 million km
B	Direct	July 1, 2016	0.3 million km
C	Retrograde (Hohmann Transfer Method)	December 5-13, 2015	0.4 million km
D	Retrograde (Gravity Brake Method)	November 22, 2015	0.3 million km

5. Conclusion

The Japanese Venus explorer, Akatsuki, performed 18 % of the planned deceleration maneuver at the VOI-1 on December 7, 2010, and now rotates about the Sun. In November 2011, it conducted maneuvers by the RCS for the period adjustment in order to meet Venus on November 22, 2015. The altitude of apoapsis has to be 0.3 million km high since the residual propulsion is approximately 330 m/s. Because of this fact, the orbit of Akatsuki will be affected by the SP largely when it is inserted into near the Venus equator and it was found that the maintenance of periapsis altitude would be very difficult. So as to prevent a spacecraft from intersecting Venus, the methods to insert into (A) the polar orbit and (B) the direct orbit after one swingby are devised. However, no cases allowed a spacecraft to rotate in the retrograde direction, the same direction with the Venusian atmosphere. Hence, another case (C) Hohmann Transfer Method was devised. It maintains the altitude of periapsis even in the retrograde orbit by changing the encounter point with an additional maneuver in the interplanetary orbit, though this causes a disadvantage: the altitude of apoapsis becomes 0.1 million km higher than the one of (A) and (B). In order to solve all these problems, the Gravity Brake Method was invented. It makes the most of the SP in the sense that it makes the rotating direction of orbit opposite from direct to retrograde. This paper presented four options so far. A careful tradeoff will be conducted so that the orbit satisfies the observation and system requirements at a maximum and that Akatsuki can be inserted safely into the Venus orbit.

6. Future Work

The next problem we face is umbra duration constrained by the spacecraft system. The orbital plane of Akatsuki is separated to the one of Venus by only 0.2 degrees. When it is inserted into near the Venus equator and when the incident angle is less than 13 degrees, the apoapsis lies in near the Venus orbital plane and the long duration of umbra occurs near the apoapsis. So as to prevent the long period of umbra, some phase adjustments will be needed. The error evaluation of orbit insertion is also necessary as a future work.

7. References

[1] Nakamura, M., Imamura, T., Ishii N., et al. "Overview of Venus Orbiter Akatsuki." Earth, Planets and Space, Vol. 63, pp. 443-457, 2011.

[2] Hirose, C., Ishii, N., Yamamoto, T., Kawakatsu, Y., Ukai, C., Terada, H., Ebara, M. "Orbital Design Strategies for Akatsuki Mission." Proceedings 28th International Symposium on Space Technology and Science – 28th ISTS. Okinawa, Japan, 2011.

[3] Kawakatsu, Y., Campagnola, S., Hirose, C., Ishii, N. "An Orbit Plan toward Akatsuki Venus Reencounter and Orbit Injection." 22nd Space Flight Mechanics Meeting, Charleston, SC, 2012.

[4] Kinoshita, H. "Celestial Mechanisms and Orbital Dynamics." University of Tokyo Press, 1998.

[5] Murray, C. D., Dermott, S. F. "Solar System Dynamics." Cambridge University Press, 1999.